

## LA-UR-19-30121

Approved for public release; distribution is unlimited.

Title: Hydrocode Modeling of Impact Craters

Author(s): Caldwell, Wendy Kaye

Intended for: University of Tennessee Junior Colloquium

Issued: 2019-10-07

---

**Disclaimer:**

Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by Triad National Security, LLC for the National Nuclear Security Administration of U.S. Department of Energy under contract 89233218CNA000001. By approving this article, the publisher recognizes that the U.S. Government retains nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy. Los Alamos National Laboratory strongly supports academic freedom and a researcher's right to publish; as an institution, however, the Laboratory does not endorse the viewpoint of a publication or guarantee its technical correctness.

# Hydrocode Modeling of Impact Craters



**Wendy K. Caldwell**

University of Tennessee  
Junior Colloquium  
October 10, 2019

[wkcaldwell@lanl.gov](mailto:wkcaldwell@lanl.gov)



Managed by Triad National Security, LLC for the U.S. Department of Energy's NNSA

# Impact Cratering

Dominant geologic process for solids in solar system

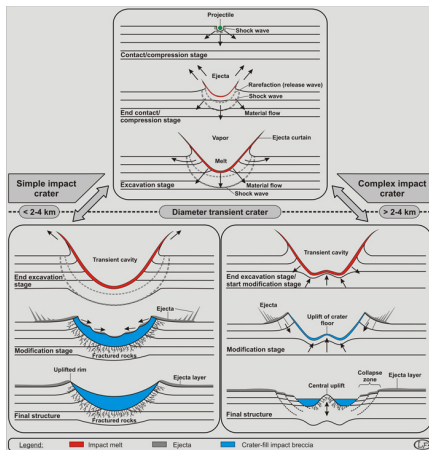
Types of impact craters:

- Simple
  - Diameter  $< 3$  km on Earth,  $< 15$  km on moon
  - Floor consists of breccia
  - Meteor Crater (Arizona)
- Complex
  - Diameter  $> 3$  km on Earth,  $> 20$  km on moon
  - Central peaks (collapsed bowl-shaped crater)
  - Floor has highly shocked and melted debris, melt pools sometimes
  - Flynn Creek Crater (Tennessee)
- Multiring basins
  - Diameter 100s to 1000s of km
  - Multiple concentric circular scarps



# Stages of Impact Cratering

1. Contact and compression: transfer of energy and momentum, shock waves
2. Excavation: target material vaporized or ejected from crater, creating ejecta blanket
3. Modification: debris flows down toward center of crater (crater collapse)



# 174 Known Impact Structures on Earth

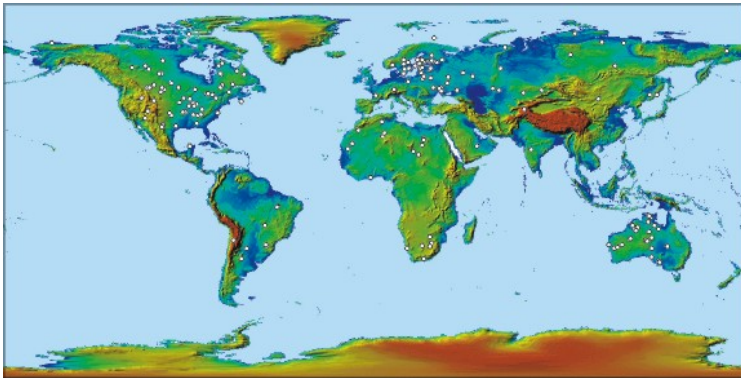


Image courtesy of University of New Brunswick Planetary and Space Science Center Earth Impact Database

# Impacts Vary by Frequency and Energy

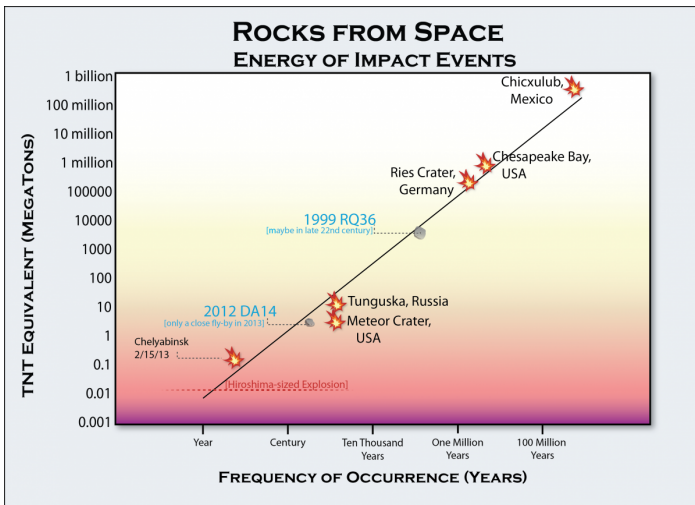


Image courtesy of LPL

# Components of Hydrocode

Lagrangian forms of conservation of momentum (1), mass (2), energy(3):

$$\frac{\rho D\mathbf{u}}{Dt} = -\nabla P \quad (1)$$

$$\frac{D\rho}{Dt} + \rho \nabla \cdot \mathbf{u} = 0 \quad (2)$$

$$\frac{dE}{dt} + P \frac{dV}{dt} = 0, \quad (3)$$

$D$ : Lagrangian differential ( $\frac{\partial}{\partial t} + \mathbf{u} \cdot \nabla$ )

EOS: relates pressure, density, internal energy

Constitutive model: stress tensor as a function of strain, strain rate effects, internal energy, damage

# Hydrocode Methods and Approaches

Discretization Methods:  
finite-difference, finite element,  
Smooth Particle Hydrodynamics  
(SPH)

Approaches: Eulerian,  
Lagrangian,  
Arbitrary-Lagrangian-Eulerian  
(ALE)

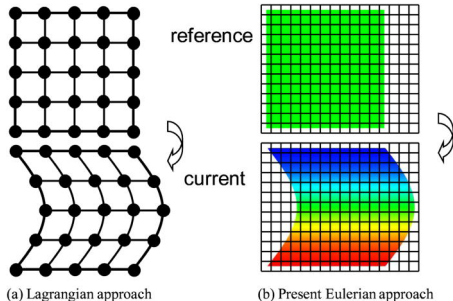


Image from  
[http://appliedmechanics.asmedigitalcollection.asme.org/  
article.aspx?articleid=1414433](http://appliedmechanics.asmedigitalcollection.asme.org/article.aspx?articleid=1414433)

# Solid Mechanics and Damage

- Strength: ability to resist changing shape
- Strain: measure of deformation
- Stress: forces that cause deformation
- Elastic and plastic properties

## Damage as an on/off switch



Image from  
<http://gamingrockson.blogspot.com/2012/09/top-5-worst-ways-to-die-in-super-mario.html>

## Damage Accumulates



Image from  
<https://i.ytimg.com/vi/AyYXWS61zEc/hqdefault.jpg>

# Why Use FLAG to Model Impacts?

## FLAG: A Big ASC Code

- Hydrodynamics code developed and maintained by LANL
- Arbitrary Lagrangian-Eulerian (ALE)
- Finite volume (conservative)
- Variety of Equations of State (EOS) and constitutive models

## Verification and Validation Problems

- Verification: 1-km diameter Al-6061 sphere impacting Al-6061 target at 5 km/s and 20 km/s
- Validation: 2-mm diameter glass sphere impacting water target at 4.64 km/s

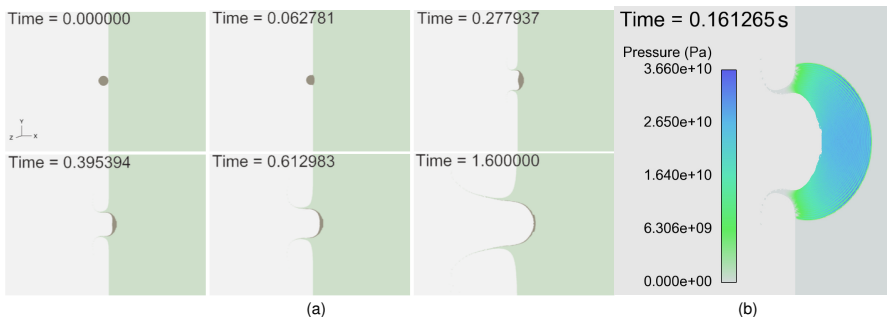
## Verification: 2D Strengthless

1D Analytic Solution	FLAG <sup>†</sup> relative error	Pierazzo, et al. Mean <sup>‡</sup> relative error	Location
5 km/s			
58.725 GPa	55.77 GPa -5.15%	40.4 GPa -33.3%	200 m into target
58.725 GPa	59.58 GPa 1.46%	—	impact point
20 km/s			
506.25 GPa	407.99 GPa -19.41%	379.0 GPa -27.50%	685 m into target
506.25	492.63 GPa -2.69%	—	impact point

FLAG results had lower errors than previously published results when comparing pressure at the same target location.



# Verification: 2D Strengthless



**Figure 6.3:** (a) Stages of impact cratering in 2D FLAG simulation of Al-6061 projectile (brown) impacting Al-6061 target (green) at 5 km/s, zoomed to show detail. (b) Pressure wave of 2D Flag simulation of Al-Al 5 km/s verification problem 0.161265 seconds after impact, zoomed to show detail.

# Verification: 2D Strength

Impact Velocity: 5 km/s

Strength Model	Maximum Pressure	Deviation from 1D Analytic
Strengthless	59.58 GPa	1.46%
Perfect Plasticity	57.96 GPa	-1.30%
Linear Hardening	57.96 GPa	-1.30%
Johnson-Cook	57.86 GPa	-1.47%
Steinberg-Guinan	57.86 GPa	-1.47%
Preston-Tonks-Wallace	57.84 GPa	-1.51%

Impact Velocity: 20 km/s

Strength Model	Maximum Pressure	Deviation from 1D Analytic
Strengthless	492.63 GPa	-2.69%
Perfect Plasticity	483.90 GPa	-4.41%
Linear Hardening	483.90 GPa	-4.41%
Johnson-Cook	483.91 GPa	-4.41%
Steinberg-Guinan	483.91 GPa	-4.41%
Preston-Tonks-Wallace	483.90 GPa	-4.41%

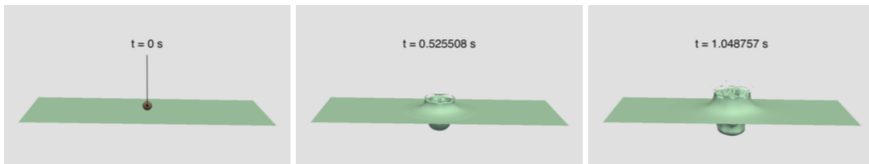
FLAG results using constitutive models resulted in lower maximum pressures than strengthless simulations, as expected.

# Verification: 3D

## Normal Impact

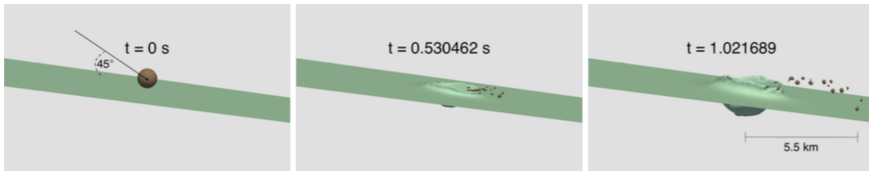
5 km/s: 52.39 GPa, -10.79%

20 km/s: 555.74 GPa, 9.78%



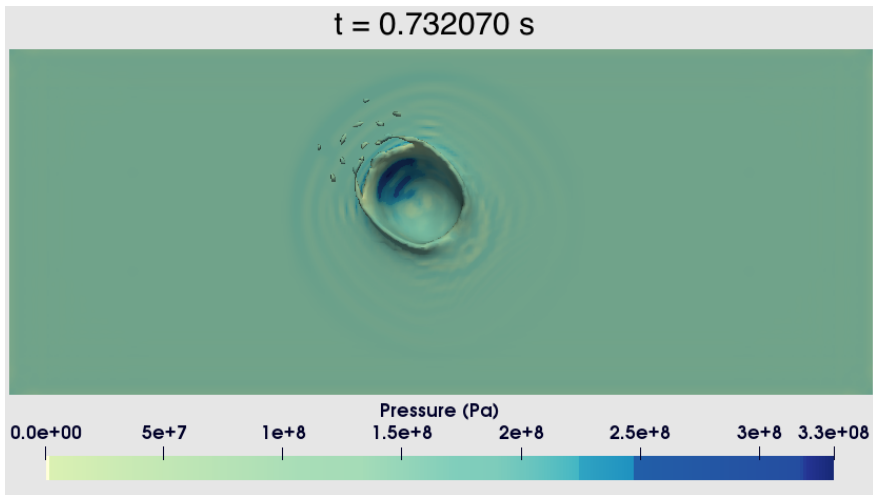
**Figure:** 3D FLAG simulation results of Al-Al 20 km/s normal verification problem.

## Oblique Impact



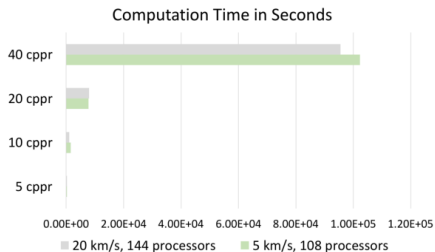
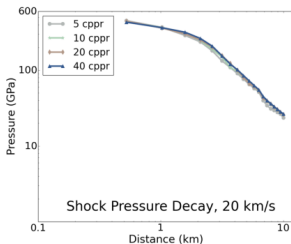
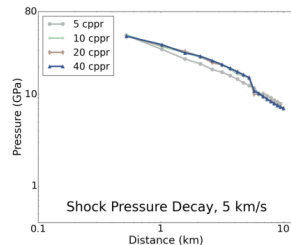
**Figure ??:** 3D FLAG simulation results of Al-Al 5 kms oblique verification problem.

# Verification: 3D



**Figure:** Pressure wave of FLAG simulation of Al-Al 5 km/s oblique verification problem 0.732070 seconds after impact.

# Mesh Resolution Study



**Figure:** (left) Shock pressure decay of Al-Al verification problem with resolutions ranging from 5 to 40 cells per projectile radius (cppr). FLAG appears to converge around 10 cppr in the 5 km/s impact and around 20 cppr in the 20 km/s impact.

**Figure:** (above) Computational times for mesh resolution study of Al-Al verification problems. The time refers to the number of seconds of simulation time needed for the pressure wave to propagate 10 km into the target. 5 km/s simulations used 108 processors, and 20 km/s simulations used 144 processors.

# Verification Summary

- 2D strengthless runs had errors between -2.69% and 1.46% at point of impact
- 2D strengthless runs had lower errors than previously published results when measuring pressure at the same location in the target
- 3D normal and oblique impacts completed in approximately 6 hours
- 3D normal impacts had errors between -10.79% and 9.78% using the coarsest tested resolution
- Mesh resolution study indicated computational time could be reduced from 28 hours to 25 minutes for some impacts

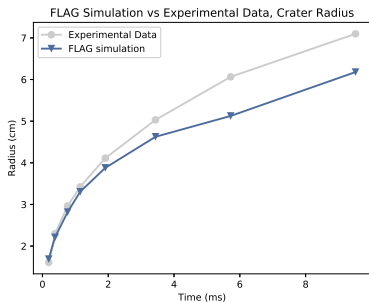
# Validation

Time (ms)	Experimental Radius (cm)	FLAG Radius (cm)	Relative Error	Experimental Depth (cm)	FLAG Depth (cm)	Relative Error
0.191	1.608	1.68713	4.92%	2.35	2.23934	-4.71%
0.382	2.297	2.20879	-3.84%	2.6	2.7669	6.42%
0.764	2.963	2.81574	-4.97%	3.32	3.44335	3.72%
1.146	3.423	3.30393	-3.48%	3.85	3.91973	1.81%
1.91	4.112	3.87845	-5.68%	4.61	4.57374	-0.79%
3.436	5.031	4.62491	-8.07%	5.39	5.52639	2.53%
5.72	6.064	5.12498	-15.49%	6.41	6.03864	5.79%
9.516	7.098	6.179	-12.95%	7.514	7.868	4.71%

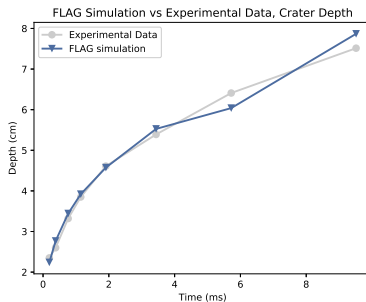
**Table:** Experimental data and FLAG simulation results for glass-water validation problem. The average error from the codes tested by Pierazzo et al.<sup>†</sup> was about -11% for crater radius and about -14% for crater depth. In comparison, FLAG had an average error of about -6.2% for crater radius and about 2.44% for crater depth.

Crater dimensions from FLAG simulations had lower average errors than previously published results using other hydrocodes.

# Validation



(a)



(b)

**Figure:** Experimental data and FLAG simulation results of (a) crater radius and crater depth (b) over time.

FLAG simulation results match experimental data well in early time, despite a resolution ranging from 0.2 to 5 cells per projectile radius (cprr). FLAG simulations results in later time underestimate radius and overestimate depth but still perform well compared to previously published results.



# Conclusions

- FLAG can be used for impact cratering simulations
- FLAG simulations can provide meaningful results at reduced computational cost
- FLAG can be used to model solid materials
- FLAG simulations match experimental data with average errors lower than previously published results

# Asteroid 16 Psyche

- Largest M-type asteroid in Main Asteroid Belt
- Upcoming NASA mission Psyche: Journey to a Metal World
- Bulk density estimates:  $1.4 \pm 0.3 - 4.5 \pm 1.4 \text{ g/cm}^3$ , some as high as  $7.6 \text{ g/cm}^3$
- Believed to be differentiated planet core
- Two large impact structures in Southern hemisphere
  - $53 \pm 15 \text{ km}$  and  $67 \pm 15 \text{ km}$  diameter
  - $6.4 \pm 0.64 \text{ km}$  depth
  - Crater formation dominated by strength rather than gravity

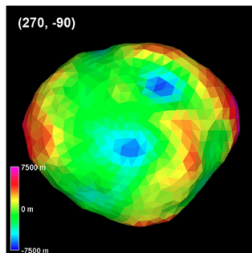
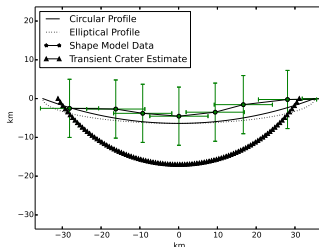


Image of Psyche with craters in blue. Image from Shepard et al., "Radar observations and shape model of asteroid 16 Psyche," *Icarus* (2017).

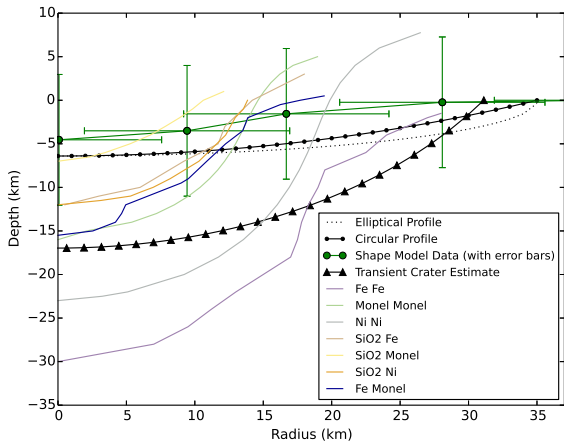
# Larger Crater: 2D Axisymmetric Simulation Setup

- Resolution  $\sim 15$  cells per projectile radius (cppr)
- $\sim 2.3$  million zones
- 180 processors
- Materials: Fe, Ni, SiO<sub>2</sub>, Monel
- Psyche: semicircle, radius 125 km
- Impactor: semicircle, radius 5 km
- Void: (500 km  $\times$  500 km square) \ (Psyche  $\cup$  Impactor)



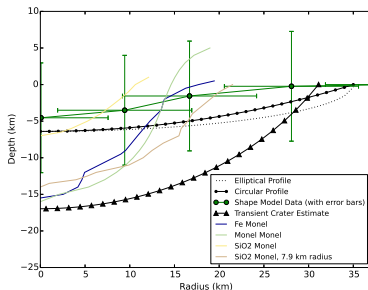
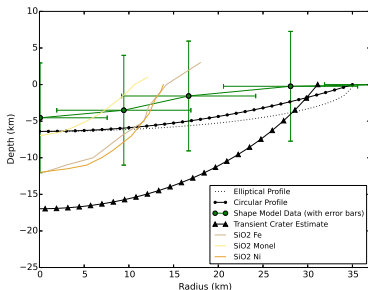
Theoretical crater profiles and shape model data for comparison.

# Larger Crater: 2D Solid Results



Crater profiles from simulations modeling Psyche as solid.

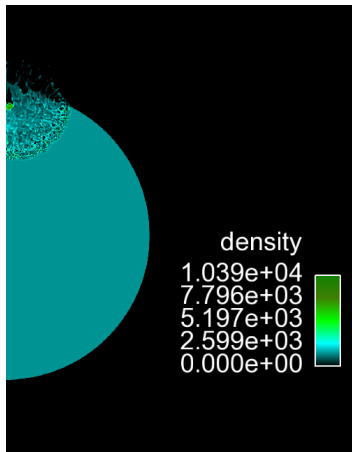
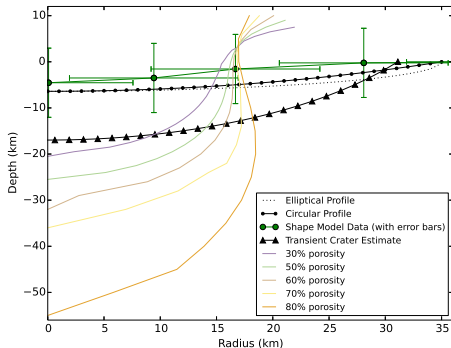
# Larger Crater: 2D Target and Impactor Studies



(Left) Target study with SiO<sub>2</sub> impactor. (Right) Impactor study with Monel target.

Crater dimensions appear to scale roughly with yield strength in the target study and density in the impactor study.

# Larger Crater: 2D Porosity Study



(Left) Crater profiles from 2D porosity study. (Right) Asteroid disruption from simulation with solid iron impacting 80% porous iron.

# Larger Crater: 2D Results Summary

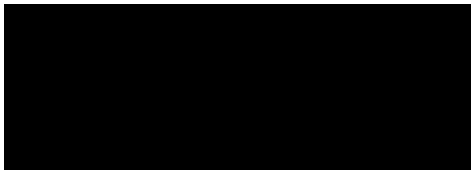


Simulation of solid  $\text{SiO}_2$  impacting solid Monel, showing the overturned flap.

- Depth overestimation and diameter underestimation  $\Rightarrow$  oblique impact angle
- Porosity study  $\Rightarrow$  porosity likely around 30%–50%
- Impactor density and target yield stress key to crater formation
- 3D simulations are needed to vary impact angle.

# Larger Crater: Psyche 3D Simulation Setup

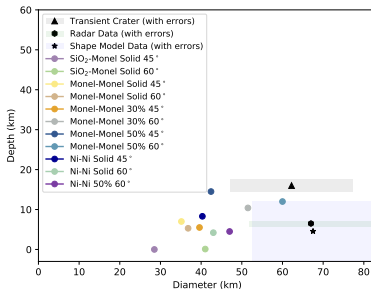
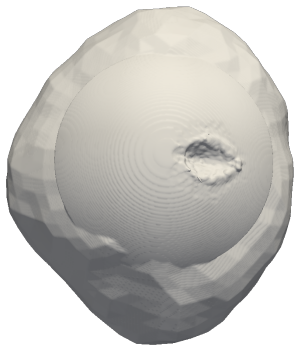
- 3D Cartesian
- Psyche: Shape model, spherical cap of radius 110 km
- Impactor: Sphere, 5 km radius
- Void: Void Box \ (Psyche & Impactor), 500 km x 500 km
- Zone size: 1000 m – 10000 m (5 cppr – 0.5 cppr)
- Zones:  $\sim$  33.4 million
- Processors: 1080



Video of Psyche simulation at initialization. Video credit: John Patchett; Shape model: Shepard et al., "Radar observations and shape model of asteroid 16 Psyche," *Icarus* (2017).

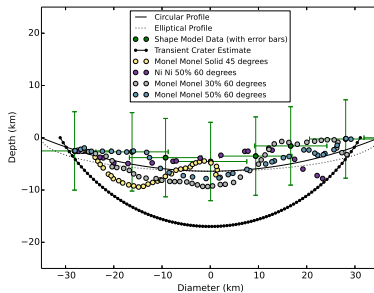
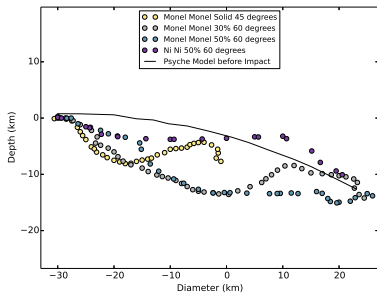


# Larger Crater: 3D Results



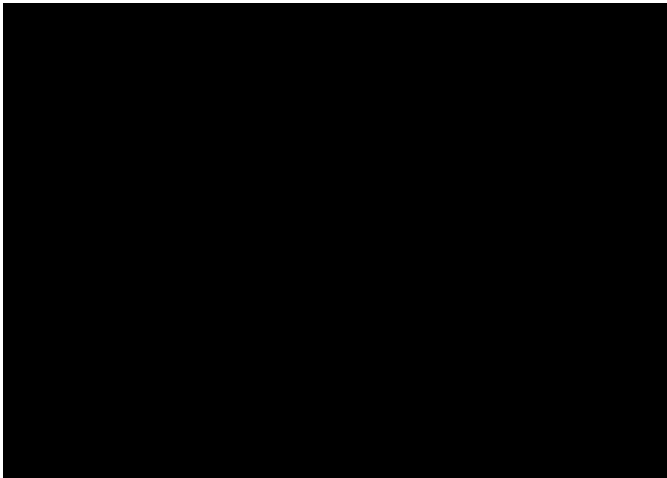
(Left) Crater formation from solid Monel impacting 50% porous Monel 60° from vertical, about 40 seconds after impact.  
(Right) Crater aspect ratios from 3D simulations, with shaded uncertainties.

# Larger Crater: 3D Profiles



(Left) Crater profiles from 3D simulations with closest matches to diameter and depth, plotted alongside the pre-impact simulation surface. (Right) Simulation profiles rotated to align with shape model for ease of comparison.

# Larger Crater: 3D Simulation Video



Simulation video of solid Monel impacting 50% porous Monel  $60^\circ$  from vertical. Video credit: John Patchett; Shape model: Shepard et al., "Radar observations and shape model of asteroid 16 Psyche," *Icarus* (2017).

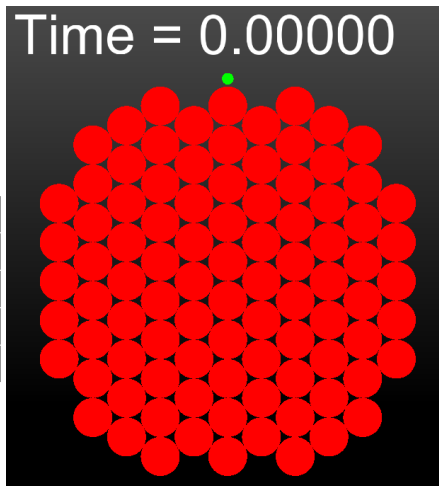
# Smaller Crater: Preliminary Results

Rubble pile: hexagonal packing

Circle radius: 12.5 km

Macroporosity: 7.7%

Microporosity	Bulk Density
0 %	8129.643 kg/m <sup>3</sup>
30 %	5690.750 kg/m <sup>3</sup>
40 %	4877.786 kg/m <sup>3</sup>
50 %	4064.822 kg/m <sup>3</sup>



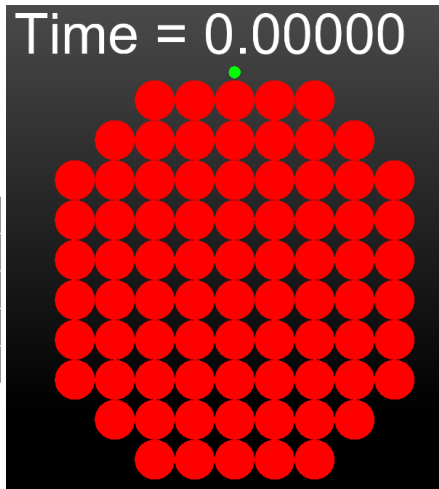
## Smaller Crater: Preliminary Results

Rubble pile: square packing

Circle radius: 12.5 km

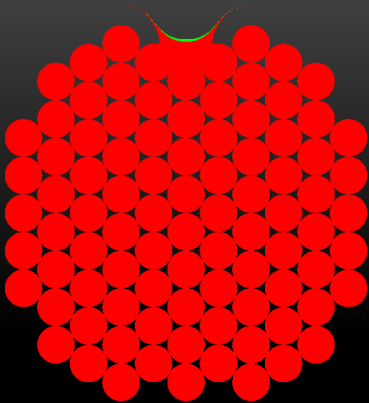
Macroporosity: 17.4%

Microporosity	Bulk Density
0 %	7279.883 kg/m <sup>3</sup>
30 %	5095.918 kg/m <sup>3</sup>
40 %	4367.930 kg/m <sup>3</sup>
50 %	3639.942 kg/m <sup>3</sup>

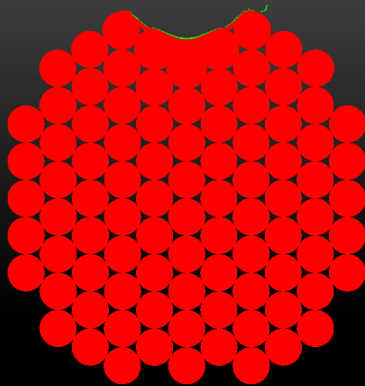


## Smaller Crater: Preliminary Results

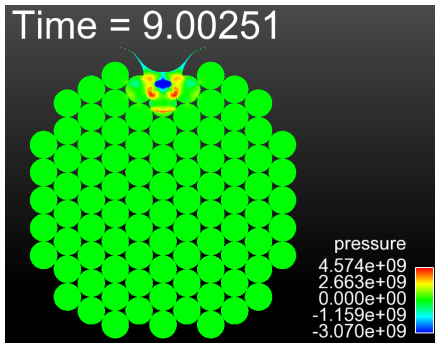
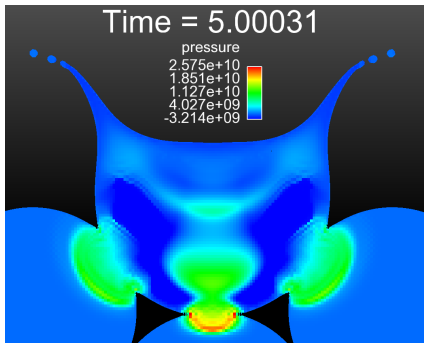
Time = 9.00251



Time = 170.00240

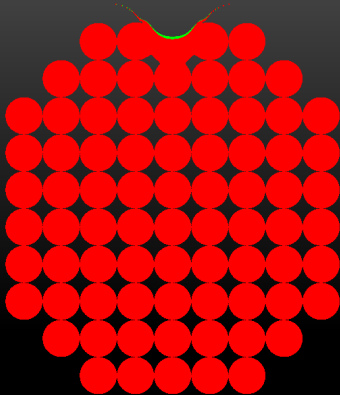


# Smaller Crater: Preliminary Results

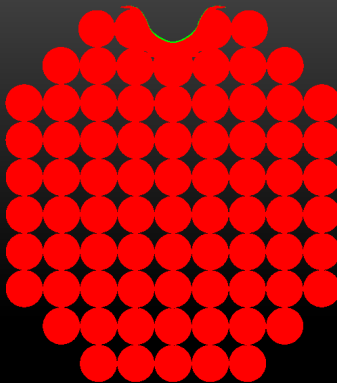


## Smaller Crater: Preliminary Results

Time = 9.00247

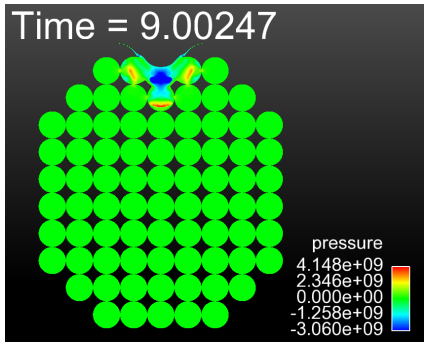
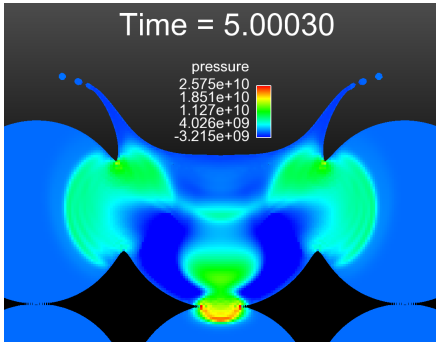


Time = 175.01137

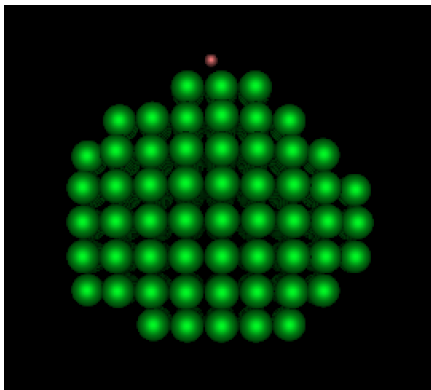
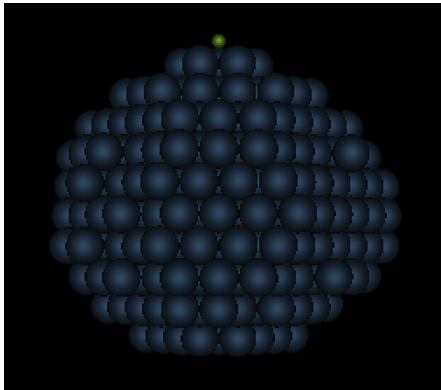




# Smaller Crater: Preliminary Results



# Smaller Crater: Forthcoming Work



# References

- Burton, D. "Consistent Finite-Volume Discretization of Hydrodynamic Conservation Laws for Unstructured Grids," Tech. Rep. UCRL-JC-118306, Lawrence Livermore National Laboratory, Livermore, CA (1994).
- Caldwell, W. K., A. Hunter, C. S. Plesko, S. Wirkus. "Verification and Validation of the FLAG Hydrocode for Impact Cratering Simulations," *Journal of Verification, Validation and Uncertainty Quantification* 3(3):031004 (2019).
- Farinella, P. and D. R. Davis. "Collision Rates and Impact Velocities in the Main Asteroid Belt," *Icarus* 97(1):111–123 (1992).
- Holsapple, K. A. "Impact and Explosion Effects," <http://keith.aa.washington.edu/craterdata/scaling/index.htm> (2018).
- Lupishko, D. "On the Bulk Density of the M-type Asteroid 16 Psyche," *Solar System Research* 40(3):214–218 (2006).
- Oh, D. Y. et al. "Psyche: Journal to a Metal World," 52nd AIAA/SAE/ASEE Joint Propulsion Conference, p. 4541 (2016).
- Pierazzo, E. et al. "Validation of numerical codes for impact and explosion cratering: Impacts on strengthless and metal targets," *Meteoritics & Planetary Science* 43(12):1917–1938 (2008).
- Shepard, M. K. et al. "Radar observations and shape model of asteroid 16 Psyche," *Icarus* 281:388–403 (2017).

# The Lagrangian Applications Project at LANL

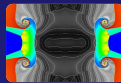
Multi-physics simulations on unstructured arbitrary polyhedral meshes

Software development (e.g. the FLAG code) for the Advanced Simulation and Computing Program

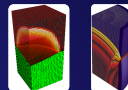
Project expertise includes fluid and solid mechanics, high explosives, mesh generation, MHD, mix and turbulence, HEDP/plasma physics, nuclear physics and engineering, and massively parallel processing and software development for supercomputers.

## Contacts:

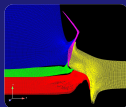
Nick Denissen ([denissen@lanl.gov](mailto:denissen@lanl.gov))  
Gabe Rockefeller ([gaber@lanl.gov](mailto:gaber@lanl.gov))



Fluid Mechanics



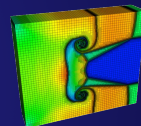
High Explosives



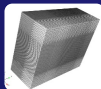
Solid Mechanics and Contact



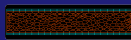
Multi-Material Hydrodynamics



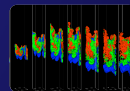
Adaptive Mesh Refinement



Structured and Unstructured Meshes



MHD and HEDP Physics



Mix and Turbulence



Operated by Los Alamos National Security, LLC for the U.S. Department of Energy's NNSA